DEFORMABLE MIRROR WITH PERIMETER WIRING

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CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 60/419,777, filed October 17, 2002, which is hereby incorporated in its entirety by reference.

BACKGROUND

Field of the Invention

[0002] This invention relates generally to deformable mirrors for an adaptive optics system, and in particular to coupling the deformable mirror to receive electric potential for causing deformations in the mirror.

Background of the Invention

[0003] There is an increasing interest in the use of free-space optical communications for various applications. For example, much of the current telecommunications infrastructure is based on the transmission of optical signals via optical fibers. While the use of fiber optics has increased the capacity and efficiency of data transmission, there are many situations where the installation of new fiber is not the best solution. As a result, there is interest in augmenting the telecommunications infrastructure by transmitting optical signals through the free-space of the atmosphere.

[0004] Free-space optical communications links can also be used advantageously in applications outside of the telecommunications infrastructure. Compared to other communications technologies, a free-space optical communications link can have advantages of higher mobility and compact size, better directionality (e.g., harder to intercept), faster set up and tear down, and/or suitability for situations where one or both transceivers are moving. Thus, free-space optical communications links can be used in many different scenarios, including in airborne, sea-based, space and/or terrestrial situations.

[0005] However, in many of these potential applications, the free-space optical communications link suffers from optical aberrations. For example, changes in atmospheric conditions can be a significant impediment to the accuracy, reliability and efficiency of free-space optical communications systems. Wind, heat waves, man-made pollutants and other effects can create constantly changing aberrations. This, in turn, can degrade the quality of the optical signal that is available at the receiver, resulting in degradation of the overall quality and efficiency of the communications channel.

[0006] To address the problem of optical aberrations, adaptive optics systems have been developed to compensate for these aberrations, thus improving the performance of free space optical communications systems. In addition to free-space optical communications, adaptive optics systems can be applied in other areas where optical aberrations are also problematic, such as for telescopes.

[0007] Some adaptive optics systems include a wavefront sensor, which senses the aberrations in the wavefront of light waves and provides a signal for correcting or compensating for those aberrations. Existing methods and devices for sensing and measuring the wavefront include several interferometric techniques, the Shack-Hartmann wavefront sensing techniques and various other systems that involve the projection of patterns of light through an optical

system. Once the wavefront senor has measured these aberrations, it can provide a signal to a device for correcting the aberrations, such as a deformable mirror. By adaptively deforming to compensate for the measured aberrations in the light waves, the optical system can correct for these aberrations.

[0008] But these techniques and systems are typically complex and expensive and have various inherent deficiencies. In addition to the deficiencies of existing wavefront sensors, the deformable mirrors that are controlled by those wavefront sensors also have a number of deficiencies. One type of deformable mirror used is a stack actuator mirror. A stack actuator mirror include a number of push rods that engage the back of a flexible mirror so that the extension and retraction of each push rod causes an associated deformation in the mirror. These rods are controlled by the wavefront sensor, which effectively controls the deformation of the mirror.

[0009] The Shack-Hartman wavefront sensor measures local slopes of various points across a wavefront, and these slopes are provided to a wavefront reconstructor. The wavefront reconstructor matches the measured slopes to generate a continuous surface for the reconstructed wavefront. This type fitting is blind to hysterisis effects in the actuators, thereby causing a waffle pattern to appear on the mirror surface. Because the push rods tend to produce a deformation in the mirror that is nearly a straight line on the mirror surface between each pair of adjacent push rods, the push rods may do a poor job deforming the mirror in a curved pattern generated by the wavefront reconstructor, especially when a small number of actuators are used. Moreover, the number of push rods, the closeness of the push rods, and the length of their travel are physically limited. Since all actuators have the same travel and are attached to a rigid reference surface, the mirror has the same stroke for all modes (i.e., low order focus has the same stroke as the highest mode produced by every other actuator being turned on and off.) For correcting the aberrations

originating in the atmosphere, this range of stroke at the highest modes is not necessary, and the corrections may not be accurate for small errors. Accordingly, the accuracy and degree of optical correction that can be applied by the stack actuator type mirror is limited.

[0010] One deformable mirror that overcomes many of these problems uses an electro-restrictive or piezoelectric material to deform the mirror in a controllable manner. Voltages are selectively applied to electrodes to deform the mirror. Connections to the individual electrodes are made by manually soldering wires to each electrode from. The wires couple the electrode to a printed circuit board, which provides voltages to the electrode for deforming the mirror. This method is difficult and time consuming, however, and can take hours to make the connections for a single mirror. Further, the connections can distort the mirror, the connected wires add mass to the mirror and therefore lower the resonant frequency of the mirror, and it is difficult to mass-produce wired mirrors using this method. Moreover, conductors carrying electricity in the same layer as the electrodes can cause an electric field that deforms the mirror in undesirable ways. Therefore, it is desirable to provide a better method for connecting the electrodes of the deformable mirror.

SUMMARY OF THE INVENTION

[0011] In an adaptive optics system, a deformable mirror having perimeter wiring avoids the deficiencies described above while maintaining reliable electrical connection with other components in the adaptive optics system. Rather than interface with associated equipment by directly connecting to the mirror's electrodes, the connection points for the electrodes are moved to a perimeter region of the deformable mirror. Therefore, the electrical connections with the mirror's electrodes are made outside a central area where the mirror is configured to receive and correct a light beam. In this way, connecting wires do not interfere electro-magnetically or

mechanically with the operation of the mirror. Moreover, electrical connections can be made much more easily to locations on the perimeter of the mirror than at various locations in a central region of the mirror.

[0012] In one embodiment, an insulating layer and a layer of conductive traces over the electrodes allow the connection points for the electrodes to be moved to a perimeter region of the mirror. An adaptive optics system comprises a deformable mirror with a reflective surface and an electrode surface. The electrode surface of the mirror includes electrodes that cause the reflective surface to deform when an electric potential is applied to one of the electrodes. An insulating layer is formed on the electrode surface of the deformable mirror and exposes at least a portion of the electrodes. Conductive traces are formed on the insulating layer, electrically insulated from the electrodes, and each conductive trace couples an electrode to a perimeter region of the deformable mirror. In this way, electrical connection can be made to each of the electrodes by connecting to the perimeter of the mirror, rather than the central region where the mirror receives light beams.

[0013] In another aspect of the invention, the deformable mirror is electrically coupled to a circuit board, from which the mirror receives electric potentials for the mirror's electrodes. Taking advantage of the perimeter connectivity of the mirror, a strip connector includes a number of electrically isolated conductors for coupling conductors on the deformable mirror to their corresponding conductors on the circuit board. To maintain good electrical contact and to stabilize the mirror, a retaining plate mechanically couples the mirror to the circuit board.

[0014] In another embodiment of the invention, a method of manufacturing a deformable mirror includes masking an electrode pattern on a back surface of the deformable mirror and depositing a conductive layer on the back surface to form electrode segments thereon. With the electrode segments formed, an insulator pattern is masked over the electrode segments, and an

insulating material is deposited over the electrode segments according to the insulator pattern. The insulator pattern exposes at least a portion of each electrode segment to allow making an electrical connection with each electrode segment. Then, a trace pattern is masked to define connections between the electrodes and a perimeter region of the deformable mirror, and a conductive material is deposited to form the conductive traces.

[0015] In addition to improving performance of the deformable mirror, moving the connections to the electrodes eliminates the labor-intensive soldering of wires to each electrode. This in turn enables larger scale manufacturing and reduces associated costs.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] FIG. 1 is a diagram illustrating a mask for depositing a number of electrodes onto an electro-restrictive layer of a deformable mirror.

[0017] FIG. 2 is a side view of the electrodes above an electro-restrictive layer of a deformable mirror.

[0018] FIG. 3 is a diagram illustrating a mask for an insulating layer for covering the electrodes.

[0019] FIG. 4 is a diagram illustrating a mask for depositing conductive traces and connection points.

[0020] FIG. 5 is a side view of the electrodes above an electro-restrictive layer, with an insulating layer, traces, and connection points.

[0021] FIG. 6 is a diagram illustrating the relationship of the traces, connection points, and electrodes.

[0022] FIG. 7 is a diagram of aside view of a deformable mirror coupled to a circuit board for receiving electric potential therefrom.

[0023] FIG. 8 is an assembly diagram for coupling a deformable mirror to a circuit board or other device.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0024] The present invention provides improved connections to the electrodes of a deformable mirror. One type of deformable mirror used in adaptive optics includes a reflective surface, a number of internal layers, and a set of electrodes on an opposite surface. In one or more of its internal layers, the deformable mirror comprises an electro-restrictive material or some other mechanism that deforms the reflective surface responsive to receiving one or more electric voltage on the electrodes. A deformable mirror of this type is described in co-pending U.S. Application No. 10/266,981, filed October 8, 2002, which is hereby incorporated in its entirety by reference.

[0025] FIG. 1 illustrates a back surface 34 of a deformable mirror 30, which is opposite a reflective surface 32 of the mirror 30. In this example, the deformable mirror 30 is formed of an electro-restrictive material 50, such as PMN, which is configured to deform upon the application of an external electric field. In an alternate embodiment, a piezoelectric material, such as PZT, may be used instead. Returning to the example of FIG. 1, deposited on a layer of the electro-restrictive material 50 are N electrodes 40-1 through 40-N. An electric voltage can be applied to the mirror 30 at one or more of the electrodes 40, thereby selectively deforming the mirror 30 and its reflective surface 32.

[0026] An insulating layer 102 having a number of holes 104-1 through 104-N is formed over the electro-restrictive material 50 and the electrodes 40. FIG. 3 illustrates a configuration of the insulating layer 102 and the holes 104. The insulating layer 102 covers at least a portion of the electrodes 40 and the electro-restrictive material 50, allowing for electrical connectivity from each electrode 40 to a perimeter region of the mirror 30. As shown FIG. 3, there is one hole 104

that corresponds to each electrode 40, exposing a portion of the electrode 40 for making an electrical connection thereto. In alternate embodiments, there could be more or less than one hole 104 for each electrode 40. Moreover, outer electrodes 40 that extend to a perimeter region of the mirror 30 may be left uncovered by the insulating layer 102, so there may be no holes 104 in the layer 102 needed for making an electrical connection to those electrodes 40. Moreover, the insulating layer 102 may cover only a portion of the electro-restrictive material 50 and electrodes 40 that is needed for making electrical connections from the electrodes 40 to a perimeter region of the mirror 30.

[0027] Over the insulating layer 102 are formed a number of conductive traces 106-1 through 106-N for electrically coupling the electrodes 40 to an external circuit. As shown in FIG. 4, each conductive trace 106 extends through a hole 104 to make electrical contact with an electrode 40 beneath the insulating layer 102. The traces 106 end at bonding pads 108 near the perimeter of the mirror. The bonding pads 108 allow for an easy and reliable electrical connection to each electrode 40 from an external circuit. FIG. 5 illustrates a side view of the mirror 30 having the traces 106 formed on the insulating layer 102 and making an electrical connection with the electrodes 40 on the electro-restrictive material 50.

[0028] FIG. 6 illustrates how each electrode 40-1 through 40-N is connected by a trace 106 to a bonding pad 108 at the perimeter of the mirror 30. In FIG. 6, the insulating layer 102 is not shown to allow illustration of how each electrode is connected. Other patterns of connecting traces 106 may be used in other embodiments.

[0029] In one embodiment, the electrodes 40 are fabricated from a base layer of Cr covered by Au, although any of a number of conductive materials can be used in the electrodes 40. The electrodes 40 can be formed on the electro-restrictive layer 50 by any of a number of conventional techniques. In one embodiment, a mask is placed on the electro-restrictive material

50, the mask defining the desired pattern of electrodes 40 to be deposited. FIG. 1 shows an example mask for forming the electrodes 40. A conductive layer is then formed on the mask, which is stripped off the electro-restrictive material 50 to leave the electrodes 40. FIG. 2 shows a side view of the electrodes 40 above the layer of electro-restrictive material 50.

[0030] In one embodiment, the insulating layer 102 is a layer of SiO_2, although other materials could also be used. A mask, such a the mask shown in FIG. 3, is laid down over the electro-restrictive material 50 and electrodes 40, and the insulating layer 102 material is deposited on the mask. The additional insulating material is then removed to expose the electrodes 40 at the holes 104 in accordance with the mask.

[0031] Once the insulating layer 102 is formed, the traces 106 can be formed thereon. In one embodiment, a photoresistive layer is placed over the insulating layer 102 in a pattern for forming the conductive traces 106. FIG. 4 shows an example mask for this purpose. The traces 106 are then formed by evaporating a metal onto the surface and stripping the mask. Alternatively, any other conventional method of forming conductive traces on a surface may be used. FIG. 5 is a side view of the mirror 30 after the insulating layer 102 and traces 106 have been formed. As shown in the figure, the traces 106 extend from the perimeter of the mirror 30 over the insulating layer 102 and through a hole 104 in the insulating layer 102 to contact the electrodes 40.

[0032] To protect the traces 106 and other layers of the mirror 30 from damage, electrical shorting, and other environmental conditions, a protective coating 110 can be formed over the layers on the back surface 34 of the mirror 30. In one embodiment, the protective coating 110 is a high-dielectric paint or other depositable material having a high dielectric value. In additional to the mechanical protection afforded by the coating 110, the coating helps to shield the electrodes 40 and traces 106 from each other and from external sources of electric fields. So that

the bonding pads 108 remain exposed for electrical connection, the pads 108 can be masked off before forming the protective coating 110.

[0033] By allowing each electrode 40 to be electrically connected at the bonding pads 108 at the perimeter of the mirror 30, the problems associated with making soldered wire connections to the electrodes 40 are avoided. The fields created by the electrical current in the traces 106 have substantially no effect on the electro-restrictive material, as the electro-restrictive material is shielded from the electric field by the electrodes 40. Because the bonding pads 108 are located at or near the perimeter of the mirror 30, connections to an external circuit can be easily made via wire bonding, clips, conducting epoxy, or even by mounting the mirror directly to a printed circuit board.

[0034] FIG. 7 illustrates one method for mounting the deformable mirror 30 and electrically coupling it to a circuit board 210. As shown in this side view, the circuit board 210 includes a number of bonding pads 215 that are coupled to circuitry for providing electric signals to the electrodes 40 of the mirror 30 to deform it. The bonding pads 215 on the circuit board 210 correspond geometrically with the bonding pads 108 of the deformable mirror 30. Taking advantage of the ability of the bonding pads 108 of the mirror 30 to align with the bonding pads 215 of the circuit board 210, a strip connector 220 is used to connect electrically corresponding bonding pads of the two sets of pads 108 and 215. In this way, and electrical device coupled to the circuit board 210 can generate and apply appropriate voltages to the deformable mirror 30, causing it to deform as desired in an adaptive optics system.

[0035] The strip connector 220 can take a variety of forms. In one embodiment, the strip connector 220 is a zebra strip connector that is bent into the circular shape of the bonding pads 108 and 215 and pressed therebetween. A zebra strip conductor is a rubber material that consists of an insulating material with a large number of small conductors that run in parallel from one

end of the strip to the other. The conductors inside the zebra strip, therefore, make an electrical connection from one end of the strip to the other, but they are electrically isolated from each other. The zebra strip connector is sandwiched between the mirror 30 and the circuit board 210, oriented so that the conductors inside the zebra strip run between the mirror 30 and the circuit board 210. Because the size of the conductors in the zebra strip is small compared to the diameter of the bonding pads 108 and 215, this configuration precisely couples each bonding pads 108 on the mirror 30 to its associated bonding pad 215 on the circuit board 210. Conductors within the zebra strip that do not align with a pair of bonding pads 108 and 215 are electrically isolated and are therefore not an operational part of the circuit.

[0036] As an alternative to using a zebra strip connector, other connectors such as flexible circuit boards can be used to couple the mirror 30 to the circuit board 210. In another embodiment, the mirror 30 is coupled directly to the circuit board 210 without the use of a strip connector 220.

[0037] To maintain good electrical contact between the mirror 30 and the circuit board 210, the strip conductor 220 is compressed therebetween. To provide an even compressive force, an o-ring 230 and a retaining plate are placed over the mirror 30 as shown in FIG. 7. The retaining plate has an open central region 245 so that light can travel past the plate 240 and the o-ring 230 to reflect off the mirror 30. As an alternative to an o-ring 230, another resilient material or one or more spring elements can be used to modulate the force applied by the retaining plate 240. To apply a force compressing the strip connector 220 between the mirror 30 and the circuit board 210, the retaining plate is mechanically coupled to the circuit board. In one embodiment, this compressive force is achieved by attaching the retaining plate 240 to the circuit board 210 by a plurality of screws 250, as shown. By pressing the mirror 30 against the circuit board 210, the strip connector 220 is maintained in good electrical contact with both sets of bonding pads 108

and 215. Another benefit of this configuration is that the perimeter of the mirror 30 is held firmly in place, leaving a central region to deform without mechanical interference from the mounting system.

[0038] FIG. 8 shows an assembly drawing of one implementation of the deformable mirror 30 mounted to a circuit board 210. The circuit board 210 includes a plurality of bonding pads 215, which receive signals to control the deformation of the mirror 30 from other components in the adaptive optics system (not shown). An inner retainer 260 and an outer retainer 265 are used to keep the strip connector 220 in place and aligned with the bonding pads 215 on the circuit board 210. The mirror 30 is then placed in contact with the strip connector 220 and is held in place with an o-ring 230 and retaining plate 240 as described above. A plate 270 can be used on the opposite side of the circuit board 210 to couple with the retaining plate 240 to avoid damaging the circuit board 210 due to the compressive force.

[0039] It can be appreciated that the bonding pads 108 on the mirror 30 correspond to particular electrodes 40, which in turn deform the mirror 30 in different ways. It is therefore important to orient the mirror 30 rotationally so that each bonding pads 108 on the mirror 30 is aligned with its corresponding bonding pad 215 on the circuit board 210. Otherwise, the wrong electrodes could be activated by the system, causing incorrect deformations in the mirror 30.

[0040] The foregoing description of the embodiments of the invention has been presented for the purpose of illustration; it is not intended to be exhaustive or to limit the invention to the precise forms disclosed. Persons skilled in the relevant art can appreciate that many modifications and variations are possible in light of the above teachings. It is therefore intended that the scope of the invention be limited not by this detailed description, but rather by the claims appended hereto.